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B71 07014

from: A. C. Buffalano, M. L. Kratage, R. D. Sharma

subject: Interpretation of Visual Observations of Apollo Water Dumps - Case 340

ABSTRACT

Mathematical models of ice cloud dynamics and thermodynamics were used to interpret visual observations of water dumps during the Apollo 12 and 13 missions. We tested several hypotheses to explain the reported size and magnitude history of the ice cloud. However, we found that the magnitude history could be explained only with the assumption that the observers were responding to the peak brightness of the cloud rather than to the integrated brightness. Taking the bulk velocity of the ice particles to be 600 cm/sec, as expected from vacuum chamber simulations we show that particle thermal velocities of 120-200 cm/sec, particle radii of 700μ and particle lifetimes of 1000 minutes are not inconsistent with the data. In previous studies these models had been used to analyze photographs of Apollo oxygen releases, and we obtained similar values for the size of the particles and for the ratio of the bulk velocity to thermal velocity. Lack of photometric data on water precludes more firm conclusions at this time, and the models cannot be tested in greater detail with the present data which has a relative error of approximately one magnitude.

(NASA-CR-119672) INTERPRETATION OF VISUAL OBSERVATIONS AT APOLLO WATER DUMPS (Bellcomm, Inc.) 18 p

N79-73195

Unclas
00/66 12866

FF No. 602(C)
18 (PAGES)
CR-119672 (NASA CR OR TMX OR AD NUMBER)
51 (CODE)
30 (CATEGORY)
AVAILABLE TO U.S. GOVERNMENT AGENCIES ONLY

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MEMORANDUM FOR FILE

Introduction

During recent Apollo flights several attempts have been made to observe the Environmental Control System waste water dumps. These dumps are made daily during translunar and transearth flight as part of the normal operations aboard the spacecraft (Cappellari and McLaughlin).

The first water dump to be observed successfully from the ground occurred during the Apollo 12 mission on November 15, 1969, at 4:03 Universal Time. The spacecraft was 110,000 kilometers from the earth. At that time 26.6 lbs. of water were dumped from the spacecraft in 11 minutes. This water dump was photographed from three locations: 1) at the Mt. Hopkins station of the Smithsonian Astrophysical Observatory (SAO) in Las Cruces, New Mexico, with a Baker-Nunn camera; 2) by Justus Dunlap at the Corralitos Observatory, also in Las Cruces, with a 24" Cassegrain telescope and an image orthicon; and 3) at the Fernbank Science Center in Atlanta, Georgia, with a 36" Cassegrain telescope and an image orthicon. James Young of the Table Mountain Observatory in California observed the cloud visually with a 24" Cassegrain telescope for an hour.

During the Apollo 13 mission, Michael Charette and Thomas Troland also observed a water dump using the 18" refractor at the Amherst College Observatory, Amherst, Massachusetts. The dump occurred at 2:12 UT on April 12, 1970, when 23.4 lbs. of water were released in ten minutes, approximately 63,000 kilometers from the earth.

The Smithsonian photographs and the image orthicon data are not yet available for analysis. This report will concentrate on the Apollo 12 and Apollo 13 visual observations.

The Data

James Young's data from the Apollo 12 mission is given in Figure 1. The diameter and visual magnitude of the cloud were reported as a function of time. The data obtained from Apollo 13 by Michael Charette and Thomas Troland is summarized in Figure 2. The visual magnitude, the range, and sketches of the shape of the cloud are given as a function of time. For both flights the shape of the cloud was described as an extended diffuse object like a nebula rather than as a point source like a star.

Analysis

The visual magnitude of a cloud with total scattering cross section, σ, and range, R, can be written as

$$m(t) = m_{\odot} + 2.5 \log_{10} \left\{ \frac{R^2(t)}{\sigma(t)} \right\} \qquad (1)$$

where $m_{\odot}$ is the solar magnitude (-26.5^{m}). Using equation (1), the spacecraft ranges, and the magnitudes reported in Figures 1 and 2, the total scattering cross section can be calculated for each observation. These are shown in Figure 3. The Apollo 13 observer admitted that relative to the spacecraft, the reported cloud magnitude could easily be in error by one magnitude and that it perhaps was more in error toward the end of the observation. Quoting the observer "Absolute magnitude estimate could be wrong by two magnitudes." The error bars on the total cross sections shown in Figure 3 correspond to an error of one half magnitude in visual estimation.

Since the amount of water in both dumps is essentially the same, and since we believe the clouds to be physically similar, we expect the scattering cross section of the cloud to be the same in both cases. From the fact that the Apollo hardware and flow rates are the same, we conclude that the ice particles have the same size, dynamics, and thermodynamics. We attribute part of the difference seen in Figure 3 to the inability of the observers to estimate the visual magnitude of the extended objects because they had no nearby nebulae or diffuse star images for a reference. Since the slopes are approximately

the same, we conclude that while the observers could not fix a visual magnitude on the cloud they were responding to changes in the appearance of the cloud in similar fashion.

The total scattering cross section of the cloud is

$$\sigma = \sigma_p N \tag{2}$$

where N is the number of visible scattering particles and σ_p is the single particle scattering cross section. Previous investigations (Kovar 1969) indicate that particle radii are about 1000μ, so the scattering cross section is approximately the geometric cross section. At least 15% of the liquid released must be converted into gas to freeze the liquid. If we assume that no more is converted into gas and initially the observers can see all the ice particles, then the initial mean particle size is roughly

$$r_o \sim 0.85 \cdot \frac{3M}{4\rho\sigma(0)}$$

$$= \frac{2.55 \times (26 \times 454)\,gm}{4 \times \frac{1\,gm}{cm^3} \times 10^5\ cm^2} \tag{4}$$

$$= 750\mu$$

where M is the total mass of the released liquid and ρ is the particle density. This is consistent with previous results and supports our physical assumptions.

There are two mechanisms causing the total scattering cross section of the cloud to change. First, the ice particles are subliming so their individual scattering cross sections are changing and second, as the particles fly off into space, the photons they scatter are eventually swamped at the observer's eye by photons scattered in the earth's atmosphere. That is, the number of visible scattering particles is decreasing and the brightness of the cloud is falling below the brightness of the sky background.

The first effect is easily included in our mathematical model. These ice particles strongly absorb in the infrared and get most of their energy from the sun. The earth emits strongly in the infrared, but at the ranges of the Apollo 12 and 13 releases, the earth's flux is much less than that of the sun. The particles lose energy by radiating it into space like black bodies and subliming. Balancing these processes (Sharma and Buffalano 1971) at the ranges of Apollo spacecraft leads to the conclusion that the particle radii are given by

$$r(t) = r_o \, e^{-t/\tau} \tag{5}$$

where τ is about 1000 minutes.

If sublimation were the only mechanism causing the change in the cross section of the cloud, then (2) would give:

$$\sigma(t) = \frac{2.55M}{4\rho r_o} \, e^{-2t/\tau} \tag{6}$$

This function is shown in Figure 3 labeled "Change Due to Sublimation Alone", and it is clear that sublimation alone cannot explain the observations.

It is difficult to estimate the effect of particle dispersion with visual observations alone. To understand why, consider the hypothetical brightness traces in Figure 4. Two are shown, one from an early stage of the expansion when the cloud is small and bright and the other from a later stage when the cloud is larger and dimmer. The sky background brightness level is also shown. If these scans had been obtained from film, the brightness above the background level could have been integrated to give the photographic magnitude. Ice particles in the region below the background would have been lost. The human eye, however, may not be able to see the cloud edges in the early case because of the bright central peak. The observer might report magnitude and size measurements different from those that would result from analysis of a photographic plate. This may be less so in the later case when the cloud brightness is not too far above the background brightness.

We tested four hypotheses concerning the visual observations. We assumed first that an observer always saw to some fixed percentage of the peak brightness as long as it was larger than the background. Second, we considered the possibility that the observer always saw to the background brightness, and third, we assumed that the observer saw to a brightness level indicated by the size reported. We were unable to fit the data by using any of these three hypotheses about the visual observation. Fourth, we assumed that the reported magnitude is not related to the actual brightness integral but is a response to the peak brightness of the cloud. This assumption at least does not contradict the visual data.

We calculated the peak cloud brightness at different times using the mathematical model outlined in Appendix A. This model has been used successfully to explain S-IVB oxygen cloud dynamics (Buffalano 1971). Several parameters describing the expansion must be known and included in the model. The cone of particles formed by the nozzle has a half angle of approximately 17° and the bulk velocity, V_o, is 600 cm/sec (Strelow 1968). We will assume that the water is released at a constant rate during the vent period and the rates are 2.42 lbs/min (Young) and 2.34 lbs/min (Charette). We also assume that the nozzle center line is approximately normal to the line of sight.

The only other parameter required is the random velocity of the particles, V_t. Assuming that the reported magnitude is actually proportional to the peak brightness of the cloud, the labeled lines in Figure 3 can be obtained for a range of values of V_t. These have been normalized at fifteen minutes after the release. It can be easily seen that large uncertainties in the visual data do not allow a precise estimation of V_t. However the theoretical description could distinguish between a choice of V_t=3 and V_t=5 if the data were of photometric quality. The fact that theoretical time histories are similar to the data suggests that our conjectures are reasonable and relatively independent of the value of the random velocity. At present we have no way of choosing a particular value for the random velocity. The cloud shapes show that the ratio of bulk velocity to random velocity appears to be larger than one, and we know that the ratio is 5 for oxygen releases. We conjecture, therefore, that the random velocity could be in the range 120-200 cm/sec.

Summary

We tested several hypotheses to explain the visual reports of the magnitude and size history of ice clouds. These

ice clouds were formed in space as a result of waste water dumps from the Environmental Control System during the Apollo 12 and 13 missions. When we assumed that the observers responded to the peak brightness of the cloud rather than to the integral brightness, the dynamic model showed no inconsistency with the data. The particle bulk velocity of 600 cm/sec, a random velocity of 120-200 cm/sec, initial radii of 700μ, and lifetimes of 1000 minutes do not contradict the data; however, other values of the parameters cannot be ruled out at the present time. It is hoped that spectrophotometric observations and photography will be attempted during the future water dumps. If visual observations are made in the future, it is highly desirable that the ice cloud be compared to a diffuse star image to obtain accurate magnitude data. This can be done by slightly defocussing the image of the star of known magnitude.

A. C. Buffalano

M. L. Kratage

R. D. Sharma

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Attachments
References
Figures 1 - 4
Appendix A

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2. Sharma, R. D. and Buffalano, A. C., "The Temperature and Size Histories of Liquid H_2, O_2 and H_2O Particles Released in Space", J. Geophys. Res., 76, p. 232, January 1971.

3. Kovar, R. P., "Light Scattering by Large Ice Particles" Symposium on Optical Contamination in Space, American Optical Soc., Aspen, Colorado, August, 1969.

4. Strelow, R. E., 1968, "Thrust Induced by ECS Fluids and Fuel Cell Purge Gases", North American Rockwell Corporation IL-69s-322-110-68-058.

5. Cappellari, J. O. and McLaughlin, W. I., "Summary of Earth-Based Observations of Apollo Water Dumps", Bellcomm Memorandum for File, B70-10018, October 2, 1970.

JAMES YOUNG, TABLE MOUNTAIN OBSERVATORY CALIFORNIA
24" CASSEGRAIN

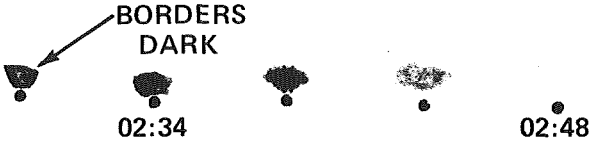
- THE DUMP BEGAN AT 4:03 UT NOV. 15. 1969
- 26.6 POUNDS OF WATER WERE RELEASED
- THE RELEASE TOOK 11 MINUTES
- THE RANGE IS APPROXIMATELY 110,000 KM

TIME FROM DUMP (MINUTES)	CLOUD DIAMETER		VISUAL MAGNITUDE (OBSERVED)	RANGE POST FLIGHT (KILOMETERS)
	ARC SEC (OBSERVED)	KM (CALCULATED)		
15	5	2.68	12	106,200
20	10	5.35	12.5 – 13	106,800
29	15	8.00	13	107,400
33	20	10.7	14	108,300
51	30	16.0	15	111,400

FIGURE 1 - APOLLO 12 DATA

MICHAEL CHARETTE AND THOMAS TROLAND,
AMHERST COLLEGE OBSERVATORY MASSACHUSETTS
18" REFRACTOR

- THE DUMP BEGAN AT 2:12 UT APRIL 12, 1970
- 23.4 POUNDS OF WATER WERE RELEASED
- THE RELEASE TOOK TEN MINUTES
- THE RANGE IS APPROXIMATELY 67,000 KM



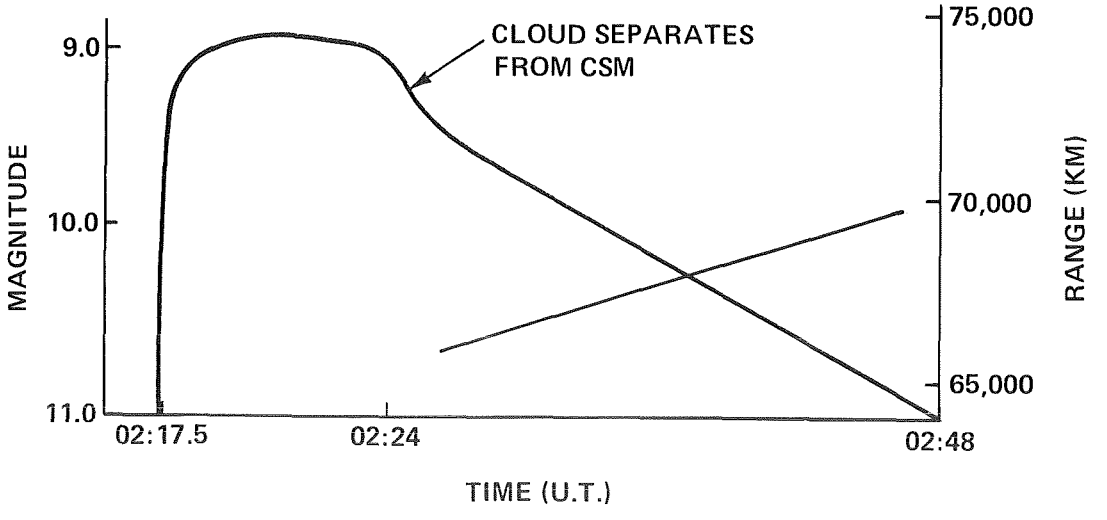


FIGURE 2 - APOLLO 13 DATA

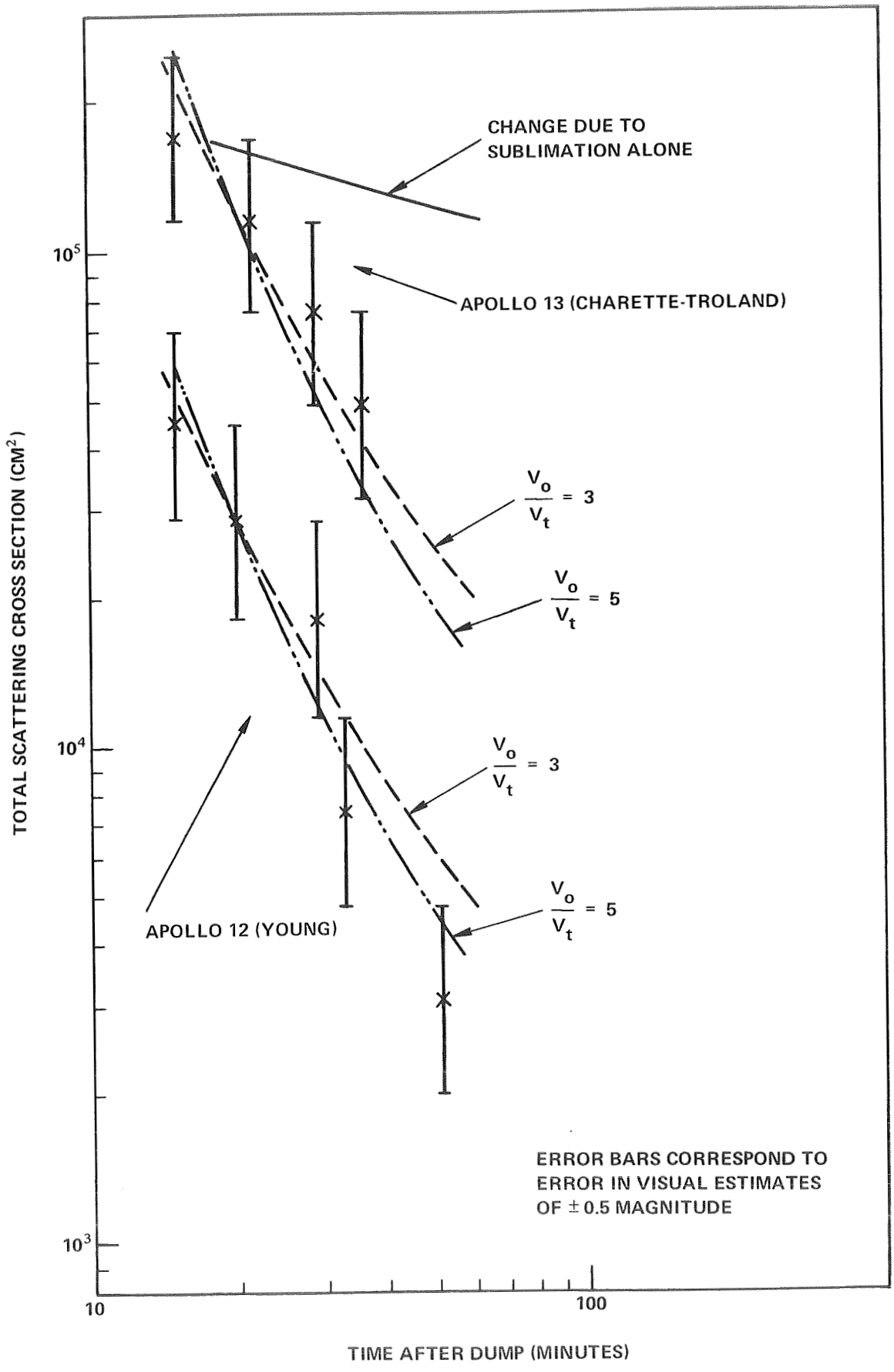

CHANGE DUE TO
SUBLIMATION ALONE
APOLLO 13 (CHARETTE-TROLAND)
$\frac{V_o}{V_t} = 3$
$\frac{V_o}{V_t} = 5$
$\frac{V_o}{V_t} = 3$
$\frac{V_o}{V_t} = 5$
APOLLO 12 (YOUNG)
ERROR BARS CORRESPOND TO
ERROR IN VISUAL ESTIMATES
OF ± 0.5 MAGNITUDE
TOTAL SCATTERING CROSS SECTION (CM^2)
10^5
10^4
10^3
10
100
TIME AFTER DUMP (MINUTES)

FIGURE 3

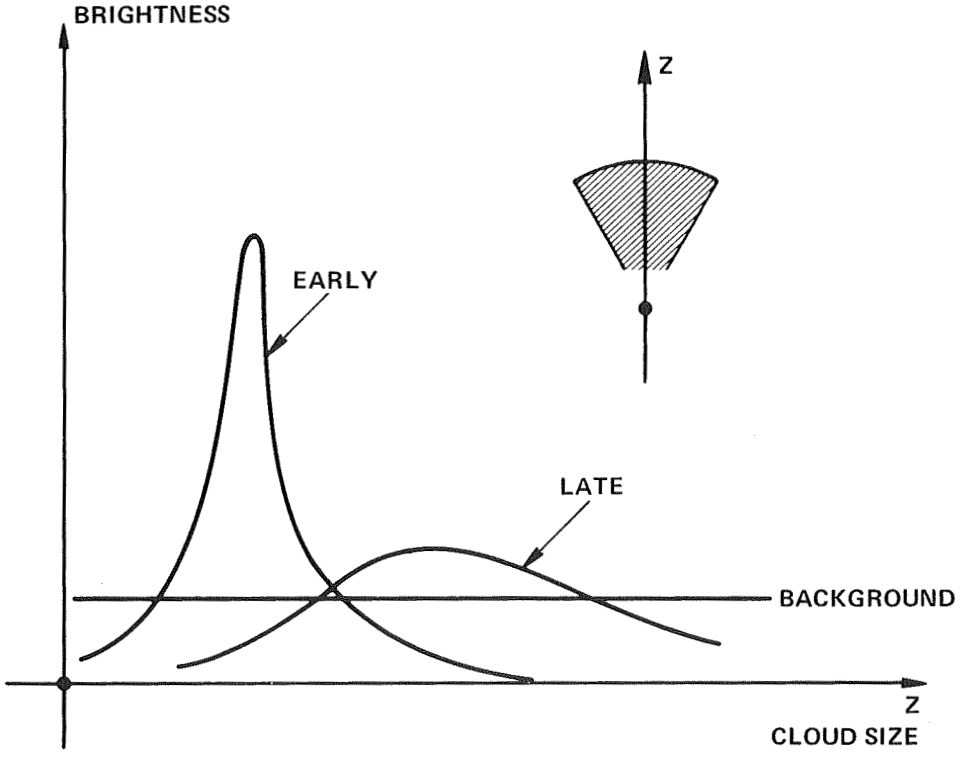


FIGURE 4 - BRIGHTNESS TRACES THROUGH A WATER CLOUD

APPENDIX A

PHYSICAL MODEL

The physical model used to reduce this data is a simple extension of a model which was used successfully to reduce Apollo oxygen data (Buffalano 1971). The original model predicted the dynamics of small oxygen particles in space after they were blown out of the S-IVB engine. Particle trajectories and the brightness of the expanding cloud were calculated.

It was shown previously (Buffalano 1971) that if particles of initial size, r_o, and density, ρ_m, with a skewed Maxwellian velocity distribution function characterized by a radial velocity, V_o, and random velocity, V_t, were all blown out of a nozzle of half angle, θ_c, at the same time and if they then expanded free from body forces and collisions, the mass density, ρ, at a field point P = (r $\sin\theta$, 0, r $\cos\theta$) as shown in Figure A1 would be given by:

$$\rho\left(\frac{r}{t},\ \theta\right) = \frac{M\ H\ \exp\left\{-V_t^{-2}\ \left(\frac{r}{t} - V_o\right)^2\right\}}{2\ \pi^{5/2}\ t^3\ V_t^3} \qquad \text{(A1)}$$

where

$$H = \frac{\displaystyle\int_o^{\theta_c} d\alpha\ \sin\alpha \int_o^{2\pi} d\beta\ \exp\left\{\frac{2rV_o}{tV_t^2}\ (\sin\theta\ \cos\beta\sin\alpha + \cos\alpha\cos\theta - 1)\right\}}{1 - \cos\theta_c}$$

M is the mass of particles released and α and β are angles locating a point in the nozzle cone.

In a continuous release, M in Equation A1 is replaced by

$$fQ(\tau)d\tau \tag{A2}$$

where $Q(\tau)$ is the total mass flow rate and f is the fraction which is converted into scattering particles. For water $f \lesssim .85$ since 15% of the liquid must evaporate to provide the energy removal which freezes the rest. Since in the subsequent expansion the number of scatterers remains constant but their mass changes as they sublime, the number density of scatterers at a point is:

$$n = \frac{\rho}{\frac{4}{3}\pi\rho_m r_o^3} \tag{A3}$$

If these have a light scattering cross section σ_p, then the differential brightness dB due to particles at the field point P is:

$$\frac{dB}{B_\odot} = \Omega_\odot \, \sigma_p \, ndl \tag{A4}$$

where $\Omega_\odot$ is the solid angle subtended by the solar disc, dl is an element along the line of sight, and the measure of brightness, $B/B_\odot$, compares the radiance, B, of an extended source to the radiance of the sun, $B_\odot$. Radiance, B, is defined as the amount of energy crossing a unit area of detector in a unit time and coming from a unit solid angle of source.

Two integrations are now required. If particles are continuously emitted between time zero and τ_c, then a time integration is performed to obtain the particle number density at time t and the measured brightness is the integral of the differential brightness along the line of sight. Therefore:

$$\frac{B}{B_\odot}(r,t) = \frac{3\Omega_\odot f}{8\pi^{7/2}\rho_m r_o^3 V_t^3} \int_{-\infty}^{+\infty} d\ell \int_0^{\tau_c} d\tau \frac{\sigma(t-\tau)H(t-\tau)Q(\tau)e^{-\left[\frac{r}{t-\tau} - V_o\right]^2 / V_t^2}}{(t-\tau)^3} \quad (A5)$$

where ℓ is the distance from the observer to the field point and the integration is performed along the line of sight. Thermodynamic considerations indicate that the scattering cross section for water during the first several hours can be represented by:

$$\sigma(t-\tau) = \sigma_o e^{-2\left(\frac{t-\tau}{\tau_s}\right)} \quad (A6)$$

where σ_o is the initial cross section and τ_s is the time scale for radius changes due to sublimation. The mass flow rate Q will be represented by:

$$Q(t) = Q_o e^{-t/\tau_q} \quad (A7)$$

in the absence of a more detailed description. Q_o is the initial flow rate and τ_q is an appropriate time scale.

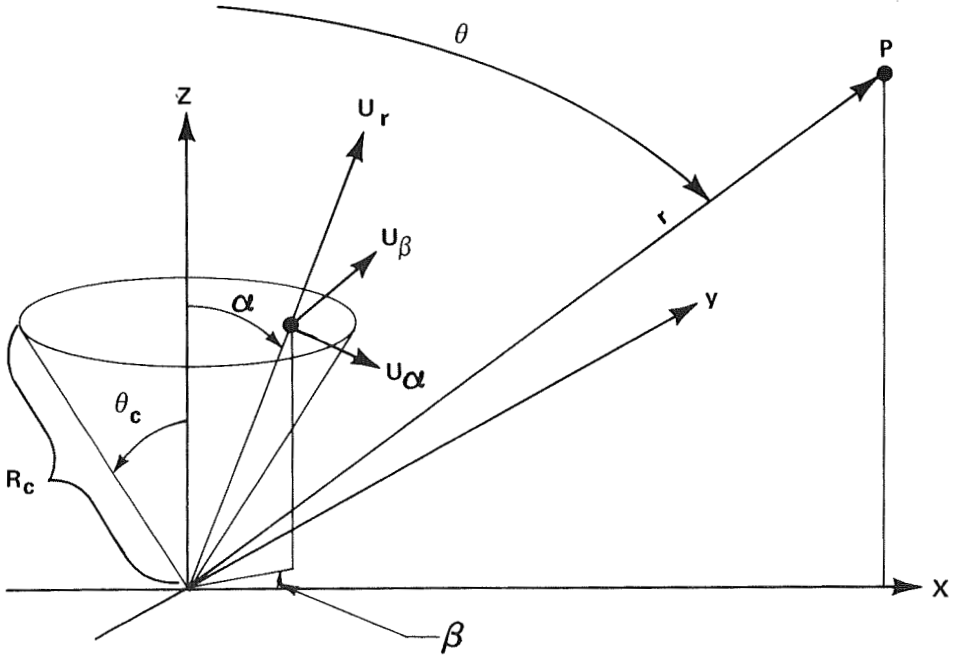


FIGURE A1 - THIS SCHEMATIC SHOWS THE COORDINATE SYSTEM USED IN THIS ANALYSIS.

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